X-611-68-352

PREPRINT

NASA TM X- 63363

THE SURVIVAL OF HEAVY NUCLEI IN COLGATE'S SUPERNOVA COSMIC RAY ACCELERATION MODEL

JAMES H. KINSEY

SEPTEMBER 1968

GSFC

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

The Survival of Heavy Nuclei in Colgate's Supernova Cosmic Ray Acceleration Model

by

James H. Kinsey*
Department of Physics & Astronomy
University of Maryland
College Park, Maryland

and

NASA/Goddard Space Flight Center
Greenbelt, Maryland

August 1968

* This work performed under NASA grant NsG-695 while graduate research assistant.

ABSTRACT

The supernova acceleration model for cosmic rays of Colgate is examined to see if heavy nuclei can indeed survive catastrophic acceleration. If it is assumed that all species of nuclei are collectively accelerated by a mechanism such as a plasma wave instability in a shock wave, then the only agent remaining to dissociate heavy nuclei in Colgate's model is the blue shifted photon flux in the radially outward moving shock wave. This would cause a sharp cutoff of the heavy component of cosmic rays from photodisintegration for cosmic ray energies greater than 10^3 GeV/nucleon.

I. INTRODUCTION:

Colgate and co-workers (1960, 1962, 1963, 1965, 1966, 1967) have developed a model for accelerating the mass of the outer mantle of a massive supernova ($M \cong 10\ M_{\odot}$) to relativistic energies, thus providing a source mechanism for the production of cosmic rays. Their mechanism is based on the formation of a strong shock wave in the supernova process which moves radially outward through the stellar envelope with increasing velocity, reaching relativistic velocities when a mass fraction equal to 10^{-4} of the total stellar mass remains external to the shock.

The shock wave is formed when the fusion process depletes the elements up through Fe in the core thus causing rapid coding of the core. To maintain equilibrium, the inner mantle of the star gravitationally collapses onto the core, raising the temperatureto an energy equivalent of $kT \approx 50$ MeV in a thin outer layer of matter of the essentially hard core material. At such high temperatures the core material quickly is reduced from a mixture which is predominantly Fe^{56}, He^{4}, p, n, and e by thermal decomposition to a mixture of p, n, and e. The energy is removed from this reaction region by neutrino emission by the process $p + e \rightarrow n + \nu$ and redeposited in a thin region external to the core by inverse β-decay. The redeposition process occurs in a thin region external to the core raising its temperature rapidly and thus producing the shock wave.

In Figure 1 is shown a plot of the shock wave's radial position as a function of time, along with the shock wave velocity. The different curves are labelled with the mass fraction external to the shock.

The temperature versus mass density is plotted in Figure 2, showing the neutrino coding of the core and heating of the inner mantle which results in the shock wave, as well as the heating of outer mantle by the shock wave.

It is noted that this described mechanism of supernova explosion is different from that of Burbidge, Burbidge, Fowler, and Hoyle (1957). The latter invoked a thermonuclear explosion as the result of the gravitational collapse heating the inner layers of the star. Colgate and White (1966) show that the change in gravitational potential energy of the imploding core is greater than that of any such thermonuclear process. They show, instead, that even should such an explosion occur, the rarefaction created by the imploding core material can "swallow" the energy of a thermonuclear explosion because the velocity of sound in the imploding matter is greater than in the external matter in an explosion.

To obtain the total amount of energy released as cosmic rays by a supernova, Colgate and White (1963) consider a 10 $M_{\odot}$ star that undergoes the supernova process, to be a type II supernova. When the mass fraction external to the shock wave is 10^{-4}, the kinetic energy of an accelerated proton is equal to its rest mass. They compute then, to a reasonable approximation, that the total energy produced in the form of cosmic rays is just $10^{-4} \times 10\ M_{\odot}c^2 = 1.8 \times 10^{51}$ ergs, for a single type II supernova. Taking the energy density of cosmic rays in the galaxy to be 5×10^{-14} erg/cm^3, the galactic volume equal to 5×10^{68} cm^3 and the cosmic ray escape time as 2×10^8 yrs, would require one type II supernova every 10^4 years. Using a higher estimate for the galactic cosmic ray energy density of 10^{-12} erg/cm^3 (Ginzburg and Syrovatskii, 1964) would require a higher frequency of type II supernovae of one every 10^2 years. These frequencies are commensurate with the currently estimated frequency of supernovae in our galaxy, hence the model is energetic enough to qualify as the source of cosmic rays.

The hydrodynamic calculations have not been explicitely extended into the relativistic region, but Colgate and Johnson (1960), used similarity solutions to compare the analytic one-dimensional problem to the three dimensional case of the supernova. Making the assumption that the material behind the shock has uniform energy per rest mass they found the proportionality

$$\mu \propto \rho^{-0.64}$$

where $\mu = \gamma - 1$ is the kinetic energy per unit rest mass and ρ is the mass density of the material. Allowing for the variation of energy per rest mass they obtained the lower limit of

$$\mu \propto \rho^{-1}.$$

With ρ and T designating the density and temperature, respectively, at the shock the mass external to the shock is

$$M(<\rho) \propto \rho T.$$

From their hydrodynamic calculations

$$T \propto \rho^{0.31}$$

so that the number of particles with energy greater than μ is given by

$$N(>\mu) \propto M(<\rho) \propto \rho^{1.31}$$

Using the upper and lower limits for kinetic energy as a function of density in this last expression they obtain

$$N(>\mu) \propto \mu^{-2 < n < -1.31}$$

which is in good agreement with the observed cosmic ray integral spectral index of n $\cong$ 1.5.

The shock conditions leading to the acceleration of the stellar matter to cosmic ray energies in Colgate's model are essentially as follows. In the shock wave itself the energy equivalent of the temperature is of the order of 10^2 KeV. The energy density in the shock wave region may be written as

$$\epsilon = RT + aT^4/\rho.$$

Using values for ρ and T from Figure 2 it is easily seen that

$$aT^4/\rho \cong 10^3 RT$$

indicating that the energy in the shock wave is almost entirely contained in the form of electromagnetic radiation with a black-body distribution of temperature T in the shock rest frame. Using the Wien displacement law for unit frequency,

$$\lambda_{max} T^{\circ} = cT/\nu_{max} = 0.51 \text{ cm } {}^{\circ}K$$

one finds that 200 KeV is equivalent to a temperature of $\cong 10^9$ °K.

In order to set an upper limit on the energy obtainable from such a radiation shock wave, Colgate and White (1963) note that the condition for the containment of the radiation is that the matter external to the shock must be a mean free path for the radiation or about 1 gm/cm^2. For their stellar model, setting

$$\int_{r}^{\infty} \rho \, dr = 1 \, gm/cm^2 = h_o \rho^{4/3}$$

with the scale height $h_o = 6 \times 10^6$ cm, they find the minimum density to be

$$\rho_{min} = 8 \times 10^{-6} \, gm/cm^3.$$

From the previous expressions for the energy spectra and mass density relations they find that $E_{max} = 3 \times 10^7$ GeV for the maximum energy that is obtainable with the above described shock wave. This is not in disagreement with current observations and the accepted view for cosmic rays of galactic origin.

One remaining critical aspect of Colgate's model is its agreement with cosmic ray charge spectra. Ginzburg and Syrovatskii (1964) reject any catastrophic mechanism, such as Colgate's, for the simultaneous rapid acceleration of both protons and heavy nuclei, their reason being that fragmentation of the heavy nuclei will occur on the proton component and specifically in Colgate's model the heavy nuclei will be destroyed through photodisintegration by the high photon flux in the shock wave. To better understand this problem, the microscopic aspect of particle acceleration in the shock wave must be considered. The mechanism presented by Colgate (1965) is acceleration of the protons and heavy ions in the electric field set up by the Compton scattering of the electrons ahead of the ions. This occurs since the radiation in the shock "seen" by the unaccelerated ions is blue shifted into the Compton region. Effectively then the shock carries along a concentration of electrons which in turn accelerate the ions.

Colgate (1965) also suggests that plasma ion waves resulting from the counter-streaming of ions of different charge-to-mass ratio could accelerate the different species of ions collectively. Two alternatives for preservation of heavy nuclei in the acceleration process are possible: (1) the original nuclei present in the pre-supernova stellar envelope are preserved intact through the shock acceleration, and (2) the heavy nuclei are destroyed by fragmentation and photodisintegration and then are re-synthesized by the neutron capture process

$$(A, Z) + N \rightarrow (A + 1, Z) + \gamma$$

$$(A + 1, Z) + P \rightarrow (A + 1, Z + 1) + N$$

in the high temperature neutron rich plasma immediately behind the shock. Colgate has determined that rapid cooling prevents the latter process from producing elements beyond $Z \approx 30$. It is necessary then to depend on the first alternative and preserve the charge spectrum through the acceleration process.

II. PHOTODISINTEGRATION OF HEAVY NUCLEI

A simple view of the charge separation in the shock is illustrated in Figure 3, with the electrons being Compton scattered toward the leading edge of the shock resulting in an electric field parallel to the shock velocity.

It has been noted by Colgate (1965) that the charge separation acceleration of the stellar material will lead to large relative velocities between protons and other nuclei whose charge-to-mass ratio is of the order of $Z/A = 1/2$. After shock passage this effect will cause fragmentation of the heavy nuclei on the proton component with a probability of survival of the heavy nuclei of the order of 10^{-2}.

As mentioned in the previous section, it is desirable then to have the acceleration of all components occur at the same rate, so that there will be no relative velocity produced between the components. Colgate suggests then that any initial counter-streaming set up between the heavy nuclei and protons will produce a two stream plasma instability, and this in turn will accelerate all components to the same velocities. If indeed the latter process will occur, then spallation is no longer a consideration in the survival of the heavy nuclei in the shock wave acceleration model.

However, there remains the problem of the photodisintegration of heavy nuclei in the blue shifted proton flux of the shock wave. The experimental threshold for the giant electromagnetic resonance is in the range of 5 to 10 MeV for the incident photons. This limit is well exceeded in the region where the stellar matter is being accelerated to cosmic ray energies.

A semi-quantitative theory of the nuclear giant resonance is discussed in several references (Blatt and Weisskopf, 1952; DeBenedetti, 1964).

This resonance, primarily resulting from the electric dipole transition, can cause the emission of a nucleon if the nucleus absorbs a photon of energy greater than the average binding energy per nucleon. The most probable reaction is the absorption of a photon and emission of a single neutron,

$$_Z M^A (\gamma, N) _Z M^{A-1}$$

For most heavy nuclei the resonance peak occurs at approximately 20 MeV, and the total cross-section for absorption of a photon at this peak energy is given by

$$\sigma_{max} \cong \frac{1}{3} A^{4/3} \times 10^{-27} cm^2 \qquad (8),$$

where A is the mass number.

A schematic representation of a typical giant resonance for an intermediate mass nucleus is shown in Figure 4. For the purposes of the present discussion it is convenient to fit a Gaussian to this curve so that integration over the cross-section with respect to energy may be facilitated. An expression that gives a reasonably good fit is

$$\sigma_d (h\nu') \cong \frac{1}{3} A^{4/3} \exp \left\{ -\frac{1}{2} \left[(h\nu' - E_m)/\Gamma \right]^2 \right\} mb \qquad (9),$$

where $h\nu'$ is the energy of the incident photon in the frame of reference of the nucleus, E_m = 22 MeV, and Γ = 2.55 MeV. Over most of the range of nuclear mass E_m will vary by only about 10% from the value given, hence the above is quite adequate for the purposes discussed here.

The electrons and nuclei see the same flux of photons in the shock wave, hence the photon flux that accelerates the nuclei through their coupling with the electrons, are also capable of causing photo-disintegration of the nuclei. If $\mathcal{F}_{ph}$ denotes the photon flux seen by the electrons and nuclei, and σ_d is the total cross-section for the absorption of a photon by a nucleus, then

$$dn_d = \mathcal{F}_{ph}\,\sigma_d\,dt \tag{10}$$

is the number of photodisintegrations that a nucleus will undergo in a time dt, during the acceleration process.

In principle it is only necessary to integrate (10) over the time of passage of the shock wave past a single nucleus to find the total number of disintegrations occurring. This, of course, requires a detailed knowledge of the shock wave structure. To make such a calculation more, or less, model independent it is desirable to make as few assumptions as possible. The approach to be taken here assumes first that Colgate's acceleration mechanism can indeed accelerate the stellar matter to cosmic ray energies, and secondly that the shock wave is coupled to the nuclei through the Compton scattering of the photons off the electrons and these in turn drag along the ions, either by means of a charge separation field, or by the creation of a two stream plasma instability.

The force on a single electron caused by the photon pressure is given by

$$F_e = \mathcal{F}_{ph}\,\sigma_c\,\Delta P_{ph} \tag{11}$$

where σ_c is the Compton cross-section and ΔP_{ph} is the momentum transferred to the electron by a single photon. Now if an ion is coupled to the electron by the charge separation field only the equation of such an ion is given by

$$\frac{dp_i}{dt} = -Z\,\mathcal{F}_{ph}\,\sigma_c\,\Delta P_{ph} \tag{12}$$

On the other hand if the ion is accelerated collectively because of the plasma instability, (12) must be rewritten as

$$\frac{dp_i}{dt} = -A\,\mathcal{F}_{ph}\,\sigma_c\,\Delta P_{ph} \tag{13}$$

where Z and A represent the nuclear charge and mass number respectively and p_i is the momentum of the nucleus.

Eliminating dt between (10) and (13) gives

$$dn_d = -\frac{1}{A}\,\frac{\sigma_d}{\sigma_c}\,\frac{dp_i}{\Delta P_{ph}} \tag{14}$$

with $\mathcal{F}_{ph}$ cancelling as well. The total number of photodisintegrating collisions that a nucleus undergoes is then obtained by integrating (14) from the initial momentum of the nucleus in the shock frame, p_i, to the final momentum as it leaves the shock, p_2, or

$$n_d = \frac{1}{A}\int_{p_2}^{p_1} \frac{\sigma_d}{\sigma_c}\,\frac{dp_i}{\Delta p_{pk}} \tag{15}$$

To evaluate the integral in (15), first consider the Doppler shift in the photon energy as seen by the electrons and nuclei,

$$h\nu' = h\nu\,(1-\beta^2)^{1/2}/(1-\beta\cos\theta') = h\nu\,(1+\beta\cos\theta)/(1-\beta^2)^{1/2} \tag{16}$$

with primed quantities referring to the rest frame of the electrons and nuclei and the unprimed quantities to the shock rest frame. A plot of (16) is shown in Figure 5, indicating that for $\beta \gtrsim 0.9$, the blue shifted radiation seen by the nuclei is confined to a core of $\theta' < 30°$. Since for greater angles than this the radiation is red-shifted to very low energies, it is justifiable to assume that the radiation seen by the particles may be treated as if it were a plane wave for $\beta > 0.9$. In this approximation (16) reduces to

$$h\nu' \cong 2\gamma h\nu \tag{17}$$

where γ is the Lorentz factor. A further approximation is to treat the photon flux as if it were monoenergetic, so that $h\nu$ represents the peak energy of the black-body radiation in the shock frame.

For a nucleus of mass AM, the differential momentum may be expressed in terms of the Lorentz factor as

$$dp_i = (\gamma^2 - 1)^{-1/2} AMc\, \gamma\, d\gamma \qquad (18)$$

The Compton total cross-section is expressed in general by the Klein-Nishina formula. For large γ however it is sufficient to use the extreme relativistic asymptotic limit of this formula (Jauch and Rohrlich, 1955):

$$\sigma_c \simeq \sigma_T \cdot \frac{1}{\alpha'} \cdot \left(\log 2\alpha' + 1/2\right) \qquad (19)$$

with σ_T = 665 mb being the Thomson cross-section, and the dimensionless variable α' is given by

$$\alpha' = 2\gamma\alpha \qquad (20)$$

with

$$\alpha = h\nu / mc^2 \qquad (21)$$

The energy of the scattered photon in the Compton process can be expressed as

$$h\nu'' = h\nu'/[1+(h\nu'/mc^2)(1-\cos\Theta')] \tag{22}$$

with Θ' denoting the scattering angle. From this one may express the net change of momentum as

$$\Delta p_{ph} = (h\nu' - h\nu'')/c = (h\nu'/c)[\alpha'(1-\cos\Theta')/(1+\alpha'(1-\cos\Theta'))] \tag{23}$$

A reasonable approximation is to take the intermediate value when $\cos\Theta' = 0$, so that

$$\Delta p_{ph} \cong (2\gamma h\nu/c)(2\alpha\gamma)/(1+2\alpha\gamma) \tag{24}$$

Substituting from (9), (18), (19), and (24) into (14) and using (17) one obtains for the total number of photodisintegrations undergone by a nucleus in the acceleration process

$$n_d = \frac{1}{6}\,\frac{A^{4/3}}{\sigma_T}\,\frac{Mc^2}{h\nu}\int_{\gamma_f}^{\gamma_i} \frac{(1+2\alpha\gamma)\exp\{-\frac{1}{2}[(2h\nu\gamma - E_m)/\Gamma]^2\}}{(\gamma^2-1)^{1/2}(\log 4\alpha\gamma + 1/2)}\,d\gamma \tag{25}$$

where γ_i and γ_f represent the initial and final Lorentz factors of the nucleus with respect to the shock wave, respectively. When the nucleus enters the shock wave it has a velocity equal in magnitude to the shock wave velocity, i.e., $\gamma_i = \gamma_s$. There is a singularity in the integral of (25) at $\gamma = 1$ which reflects the fact that an infinite time would be required for the particles to be completely stopped in the shock frame. In other words, the particles leave the shock with some residual velocity corresponding to $\gamma > 1$, in the shock frame, and the particles immediately after shock wave passage will have a velocity in the rest frame of the star of $\gamma < \gamma_s$.

Above if (12) had been substituted into (10), one would have obtained ultimately for (14),

$$dn_d = -\frac{1}{Z} \frac{\sigma_d}{\sigma_c} \frac{d\rho_i}{\Delta \rho_{ph}} \quad (26),$$

for the case of the charge separation field acceleration. It is possible then to express the result for the two cases as

$$n_{d,p} = C_p \int_{\gamma_f}^{\gamma_i} f(\gamma)\, d\gamma \quad (27),$$

and

$$n_{d,f} = C_f \int_{\gamma_f}^{\gamma_i} f(\gamma)\, d\gamma \quad (28),$$

with

$$C_p = \frac{1}{6} \frac{A^{4/3}}{\sigma_T} \frac{Mc^2}{h\nu} \quad (29),$$

and

$$C_\xi = \frac{A}{Z} C_p \qquad (30).$$

$f(\gamma)$ is just the integrand in (25).

In Figure 6, $f(\gamma)$ is plotted as a function of γ, showing the resonance peak at $\gamma = 55$ and the singularity at $\gamma = 1$. It is easily seen that the lower limit of integration γ_f may be set over a rather wide range of values such that $\gamma_f > 1$ without making any substantial difference in the result of the integral. Therefore γ_f can safely be set equal to 2 without changing the final result appreciably. This means only that the final velocity of a proton in either case, or a heavy nucleus in the plasma instability case will be equal to $\gamma_s - 1$ in the rest frame of the star where γ_s is again the shock velocity.

The integral occurring in (27) and (28), is easily performed by numerical integration. From the resulting number of collisions in each case the probability of survival of the heavy nuclei is simply

$$P(\text{survival}) \cong e^{-n_d} \qquad (31)$$

The calculations have been done for iron, with $\sigma_T = 665$ mb, $Mc^2 = .938$ GeV, and $h\nu = .2$ MeV. The results for both cases are tabulated in Table I for a range of values of the shock wave velocity γ_s. These same results are plotted in Figure 6.

It is readily seen from Figure 6, that there is little difference between the two acceleration mechanisms, but that both show a steep cutoff of heavy nuclei at approximately $\gamma_s = 35$. Along the top of the plot are scales showing the corresponding momentum per nucleon to which such particles would be accelerated by the shock wave passage. For the case of field acceleration this corresponds to about 15 GeV/nucleon, and for plasma wave acceleration to 32 GeV/nucleon.

Colgate and White (1966) noted that in the non-relativistic case the heated material behind the shock would expand adiabatically after shock passage and that its bulk velocity would double in the process, corresponding to an increase in kinetic energy by a factor of four. Colgate (1967), however, shows that in the relativistic case the final energy of the stellar matter after expansion would be proportional to γ_s^2. Taking this latter result into account, the above cutoff energies for the complete destruction of heavy nuclei would occur at 225 GeV/nucleon for the case of the field acceleration process, and 1024 GeV/nucleon for the plasma wave acceleration process.

TABLE 1. PROBABILITY OF SURVIVAL OF IRON NUCLEI IN SHOCK WAVE.

	****** FIELD ACCELERATION OF FE *********			******* PLASMA ACCELERATION OF FE ********			
GAMMA	NCOLL	ERROR	P(SURVIVAL)	NCOLL	ERROR	P(SURVIVAL)	F(GAMMA)
5	0.0000000000	0.0000000000	1.0000000000	0.0000000000	0.0000000000	1.0000000000	0.0000000000
10	0.0000000020	0.0000000000	0.9999999980	0.0000000009	0.0000000000	0.9999999991	0.0000000000
15	0.0000003624	0.0000000036	0.9999996376	0.0000001682	0.0000000017	0.9999998318	0.0000000007
20	0.0000371447	0.0000003714	0.9999628559	0.0000172458	0.0000001724	0.9999827544	0.0000000603
25	0.0022255783	0.0000222364	0.9977768965	0.0010333042	0.0000103240	0.9989672295	0.0000030733
30	0.0715233253	0.0007146257	0.9309745621	0.0332072582	0.0003317905	0.9673380501	0.0000860466
35	1.3418546453	0.0134075922	0.2613604878	0.6230039424	0.0062249535	0.5363309082	0.0013158729
40	14.4847861888	0.1447160178	0.0000005121	6.7250793020	0.0671895797	0.0012004254	0.0109552020
45	87.4737967191	0.8737256387	0.0000000000	40.6128341910	0.4056583323	0.0000000000	0.0495563029
50	315.2258880198	3.1457844937	0.0	146.3548765806	1.4605428007	0.0000000000	0.1216464515
55	724.1927057729	7.2294115896	0.0	336.2323276803	3.3565125237	0.0	0.1619006879
60	1106.0599368860	11.0299512956	0.0	513.5278278399	5.1210488158	0.0	0.1167569025
65	1315.6277295720	13.1511875995	0.0	610.8271601584	6.1059085283	0.0	0.0456045230
70	1377.0967053695	13.7448373801	0.0	639.3663274930	6.3815316408	0.0	0.0096444964
75	1435.6280052447	14.2893527253	0.0	666.5415738636	6.6343423367	0.0	0.0011040425
80	1380.0389162506	13.7968339780	0.0	640.7323539735	6.4056729184	0.0	0.0000683973
85	1402.0432690991	13.9786225445	0.0	650.9486606532	6.4900747528	0.0	0.0000022928
90	1377.5684097032	13.7690999798	0.0	639.5853330765	6.3927964192	0.0	0.0000000416
95	1393.3894743412	13.9112515201	0.0	646.9308273727	6.4587953486	0.0	0.0000000004
100	1422.7284174580	14.1873323157	0.0	660.5524795341	6.5869757180	0.0	0.0000000000

III. DISCUSSION

On the basis of the approximate treatment described in the previous section, Colgate's model permits acceleration of heavy nuclei up to quite large final kinetic energies. Since Colgate (1968a) has shown that it is not likely that the heavy nuclei can be resynthesized in the hot material behind the shock, if spallation were to occur, it seems reasonable to rule out the possibility of the field acceleration process since it would surely produce spallation. One is left then with a plasma wave process, or some other mechanism, which will collectively accelerate all nuclei to the same velocities. Such a process seems to allow acceleration of the supernova material up to kinetic energies of the order of 10^3 GeV/nucleon before photodisintegration on the photon field of the shock wave eliminates the heavy nuclei component.

At the present time experimental observations extend only as far as about 50 GeV/nucleon (von Rosenvinge and Webber, 1968) and these results show no reduction in heavies. The conclusion that is reached then is that so far Colgate's supernova acceleration is not in any appreciable disagreement with current cosmic ray observations.

It should be noted that the version of the model presented above is perhaps an extreme case. Since most supernovae are probably of mass < 10 $M_{\odot}$, this may require that some small modifications be made to the parameters. Further, according to Colgate (1968b) there may be a good possibility for resynthesis of the heavy nuclei following shock passage by means of successive rapid neutron captures followed by p, n charge exchange reactions between bound neutrons and free protons.

ACKNOWLEDGEMENT

I am most grateful to Dr. James A. Earl for bringing to my attention this particular problem and for his many helpful suggestions. Also I want to thank Drs. C. E. Fichtel, R. Ramaty and H. Ogelman for very useful discussions.

References

Allen, C. W. 1955, Astrophysical Quantities, (London: Athlone), Chap. 5.

Blatt, J. M., and Weisskopf, V. F. 1952, Theoretical Nuclear Physics, (New York: Wiley), pp. 651-659.

Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F. 1957, Rev. Mod. Phys., 29, 547.

Colgate, S. A., and Johnson, M. H., 1960, Phys. Rev. Letters, 5, 235.

Colgate, S. A., Grasberger, W. H., and White, R. H. 1962, Jour. Phys. Soc. Japan, 17, Supp. A-III, 157.

Colgate, S. A., and White, R. H. 1963, Proceedings of the International Conference on Cosmic Rays, Jaipur, Vol. 3, p. 335.

Colgate, S. A. 1965, Proceedings of the International Conference on Cosmic Rays, London, Vol. 1, p. 112.

Colgate, S. A., and White, R. H. 1966, Ap. J., 143, 626.

Colgate, S. A., 1967, Ap. J., 150, 163.

Colgate, S. A., 1968, Proceedings of the Tenth International Conference on Cosmic Rays, Calgary (in press).

Colgate, S. A., 1968b, (private communication).

DeBenedetti, S. 1964, Nuclear Interactions, (New York: Wiley), pp. 307-312.

Fermi, E. 1950, Nuclear Physics, (Chicago: Univ. of Chicago), p. 40.

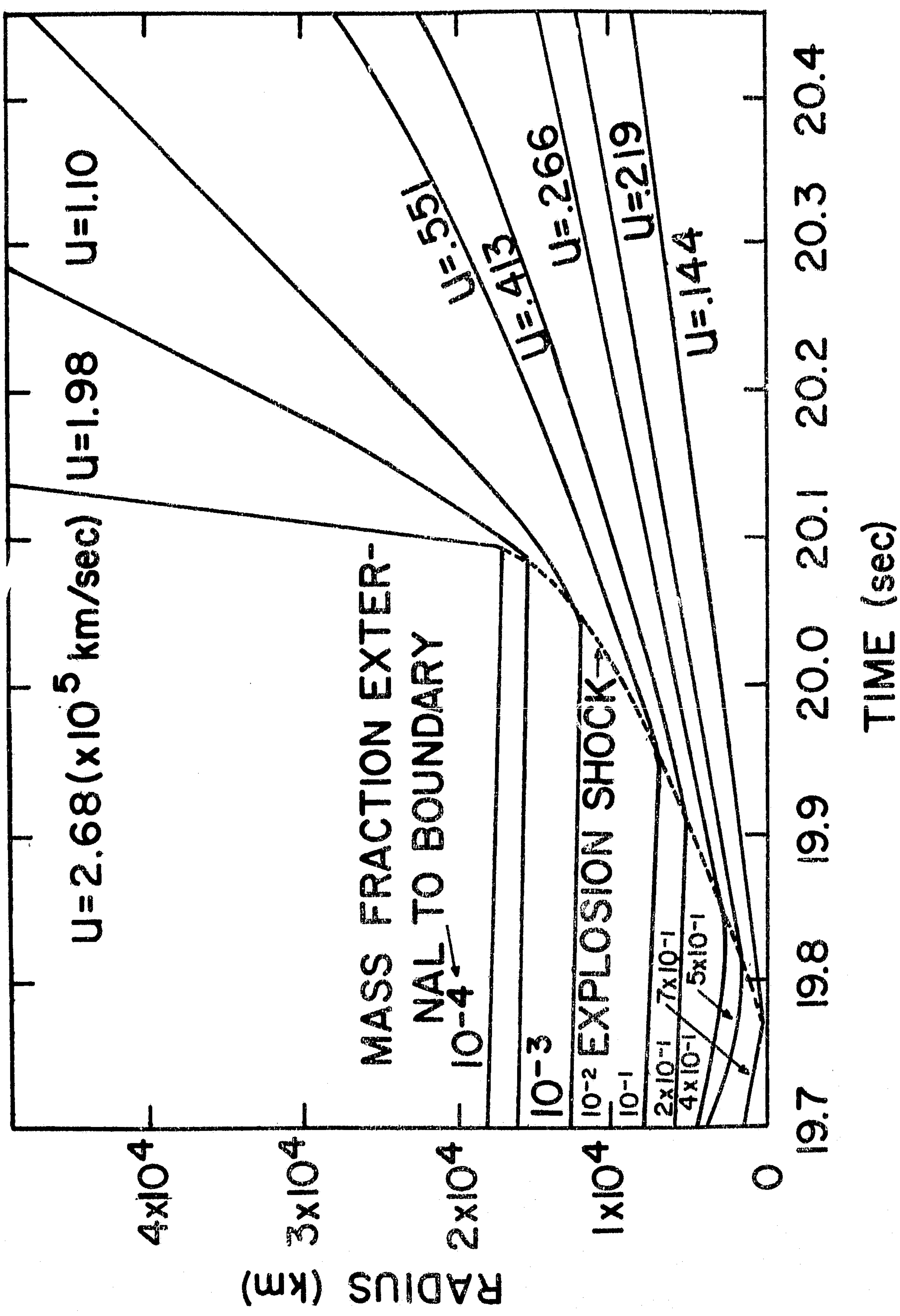
Ginzburg, V. L., and Syrovatskii, S. I. 1964, The Origin of Cosmic Rays, (New York: MacMillan), p. 153.

Jauch, J. M., and Rohrlich, F. 1955, The Theory of Photons and Electrons, (Reading, Mass.: Addison-Wesley), Chap. 11.

von Rosenvinge, T., and Webber, W. R. (private communication).

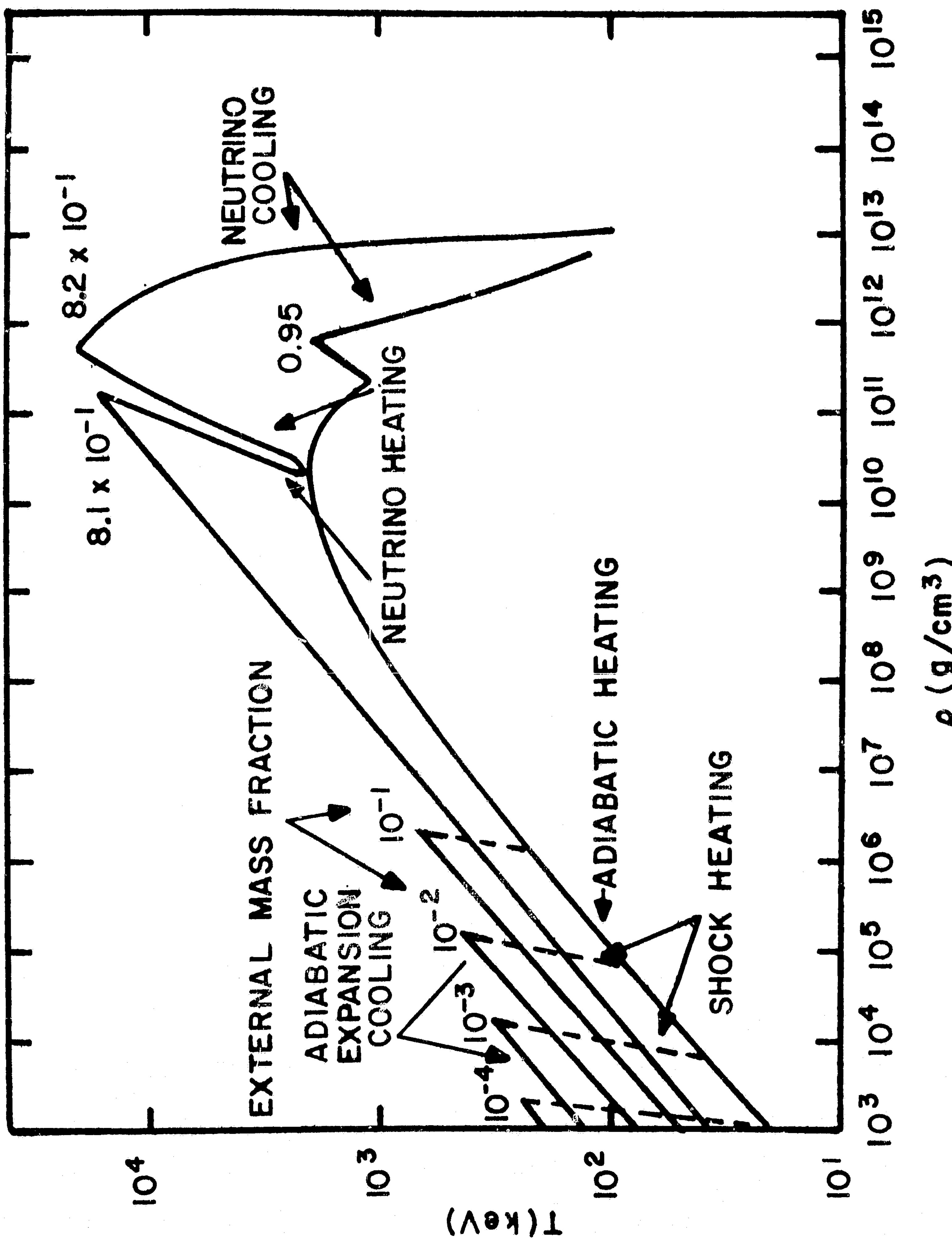
Figure Captions

Figure 1:	10 $M_{\odot}$ supernova radius versus time, (Colgate and White, 1966).
Figure 2:	10 $M_{\odot}$ supernova temperature versus density with neutrino deposition, (Colgate and White, 1966).
Figure 3:	Schematic illustration of the charge separation of ions and electrons in the shock region of a supernova, resulting in an accelerating field $\vec{E}$.
Figure 4:	Schematic illustration of qualitative theoretical expectation of the cross-section for formation of an excited nucleus by gamma-ray absorption for an intermediate nucleus, (Blatt and Weisskopf, 1952).
Figure 5:	The angular dependence of Doppler shifted radiation for various values of β.
Figure 6:	The function $f(\gamma)$ versus γ_s and the probability of survival of an iron nucleus for charge separation field acceleration and plasma wave acceleration.



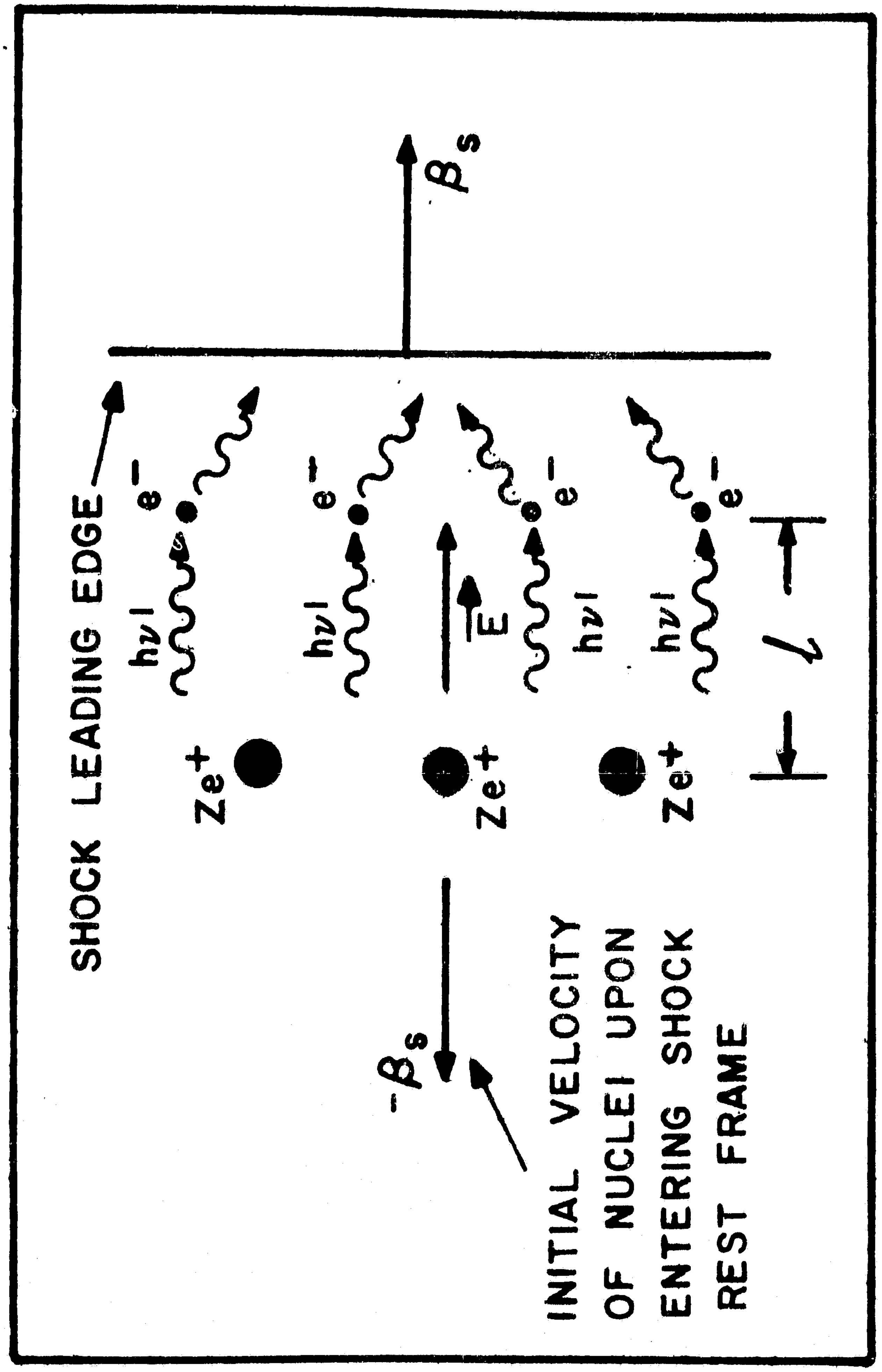
U=2.68(x10^5 km/sec)
U=1.98
U=1.10
U=.551
U=.413
U=.266
U=.219
U=.144
MASS FRACTION EXTERNAL TO BOUNDARY
10^-4
10^-3
10^-2
10^-1
2x10^-1
4x10^-1
5x10^-1
7x10^-1
EXPLOSION SHOCK
RADIUS (km)
4x10^4
3x10^4
2x10^4
1x10^4
0
19.7
19.8
19.9
20.0
20.1
20.2
20.3
20.4
TIME (sec)

Figure 1



T(keV)
10^4
10^3
10^2
10^1
ρ (g/cm^3)
10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
EXTERNAL MASS FRACTION
ADIABATIC EXPANSION COOLING
10^{-4}
10^{-3}
10^{-2}
10^{-1}
ADIABATIC HEATING
SHOCK HEATING
NEUTRINO HEATING
NEUTRINO COOLING
8.1×10^{-1}
8.2×10^{-1}
0.95

Figure 2



SHOCK LEADING EDGE
β_s
$-\beta_s$
Ze^+
$h\nu$
e^-
$\overline{E}$
l
INITIAL VELOCITY
OF NUCLEI UPON
ENTERING SHOCK
REST FRAME

Figure 3

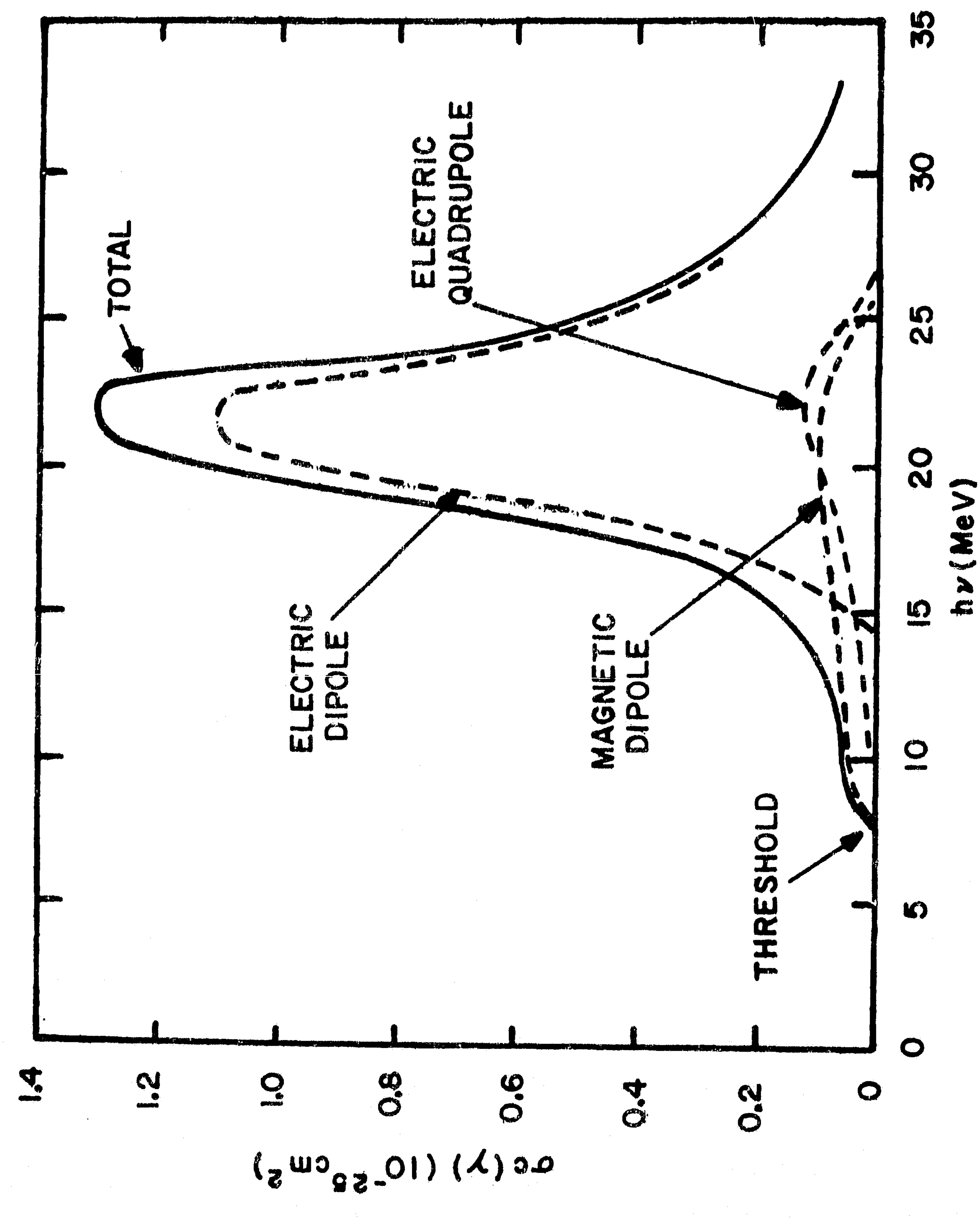
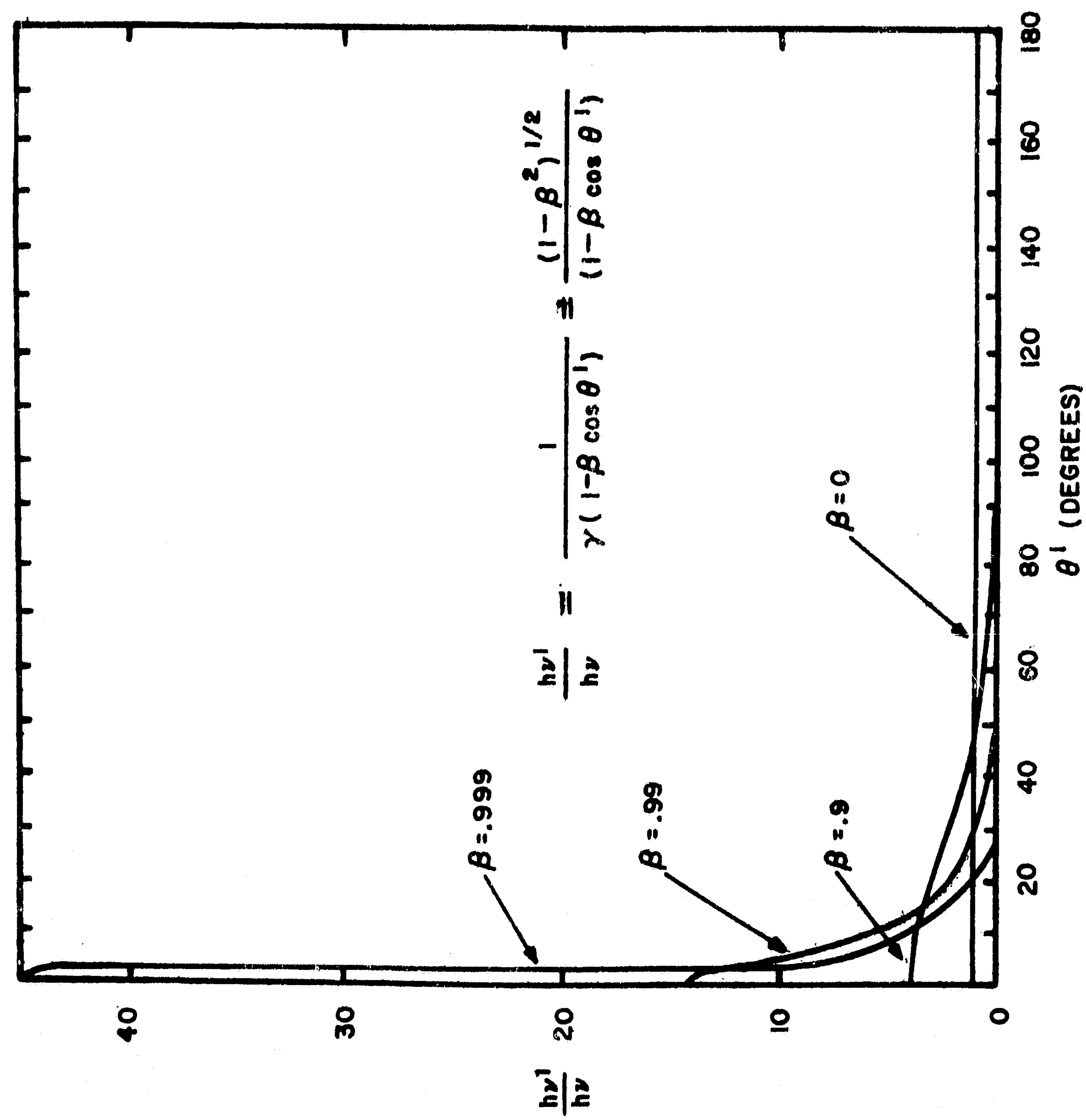

TOTAL
ELECTRIC QUADRUPOLE
ELECTRIC DIPOLE
MAGNETIC DIPOLE
THRESHOLD
hν (MeV)
0
5
10
15
20
25
30
35
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Figure 4



$\frac{h\nu'}{h\nu} = \frac{1}{\gamma(1-\beta\cos\theta')} = \frac{(1-\beta^2)^{1/2}}{(1-\beta\cos\theta')}$
$\beta = .999$
$\beta = .99$
$\beta = .9$
$\beta = 0$
$\frac{h\nu'}{h\nu}$
0
10
20
30
40
20
40
60
80
100
120
140
160
180
θ' (DEGREES)

Figure 5

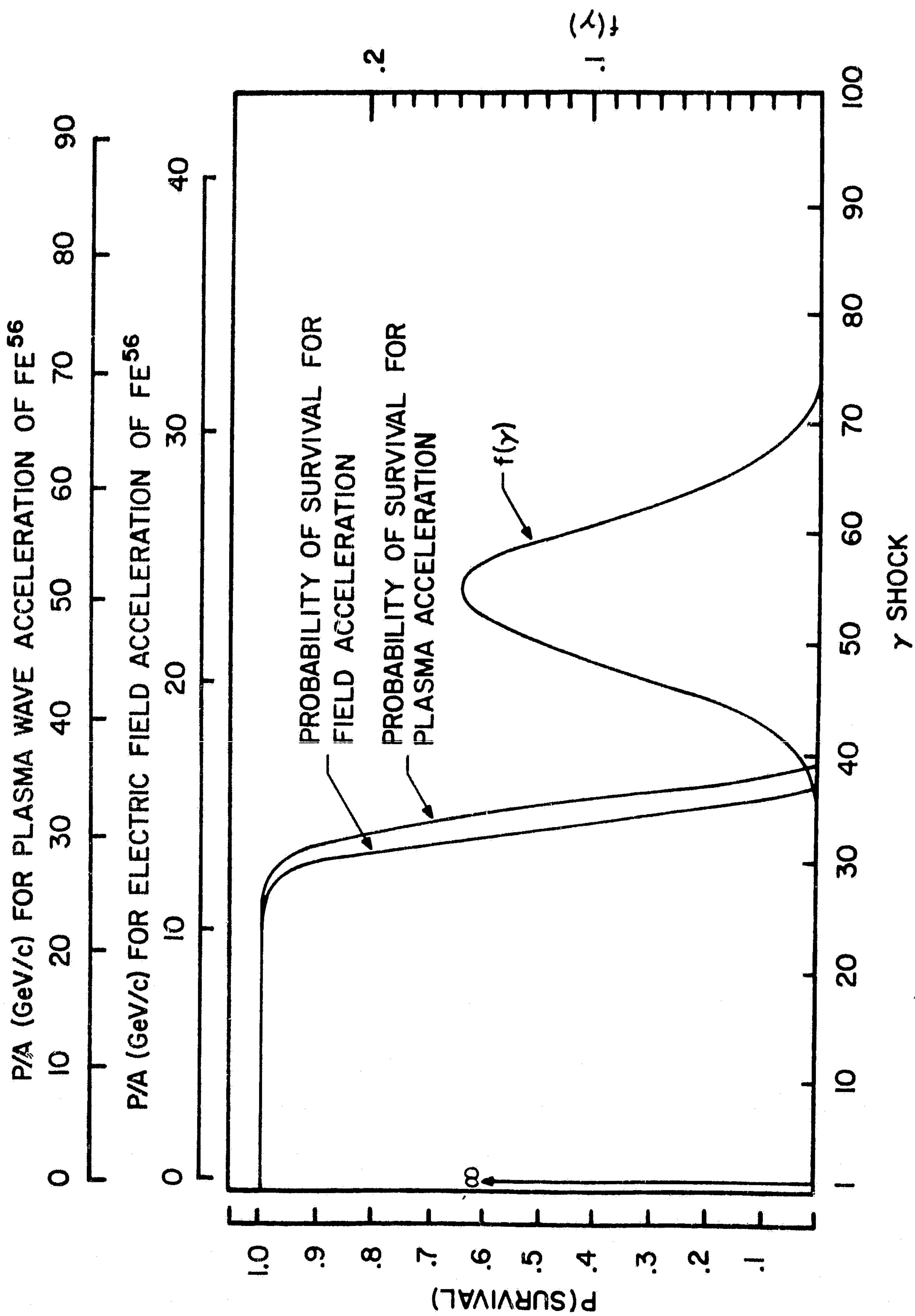

P/A (GeV/c) FOR PLASMA WAVE ACCELERATION OF FE56
P/A (GeV/c) FOR ELECTRIC FIELD ACCELERATION OF FE56
PROBABILITY OF SURVIVAL FOR FIELD ACCELERATION
PROBABILITY OF SURVIVAL FOR PLASMA ACCELERATION
f(γ)
γ SHOCK
P(SURVIVAL)

Figure 6